TRANSPORT OF POLLUTION IN THE RIVERS FLOWING THROUGH WETLAND AREAS

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Abstract: A modelling framework for the analyses of the transport of passive solutes in the rivers wandering through wetland areas has been presented. The model is based upon so called dead-zone approach used so far for relatively simple geometries. Computations for a case study of the marshy Upper Narew river valley have been shown. The results of computations are compared with the experimental data obtained from a dye tracer test performed in the protected area of the Narew river.

INTRODUCTION

A wetland area is an area that is inundated or saturated by ground or surface water frequently or for prolonged periods – often enough and long enough to support vegetation typically adapted for life in saturated soils. Such areas typically lie between a water body and uplands. Wetlands obviously serve a number of valuable functions, among them is cleaning or filtering pollutants from surface waters. It is however a problem when such wetland area is a natural habitat for a variety and wildlife and plants, including rare, threatened, endangered and endemic species. Then this cleaning function may become disastrous for such valuable area and may cause adverse secondary impacts like the wildlife mortality. Going along this line it seems that understanding of the mechanisms governing pollution transport in the river wandering through a wetland area is very important. It is believed that the fate of contaminats is, among others governed by the continuous exchange of water between stream water and the adjacent wetlands. Entrapment of a part of the pollution in a riparian wetland causes the creation of long tails in the breakthrough curves observed in the river. In other words a large portion of the contaminants in solution can be captured within the wetlands and eventually be partly (or totally) released back into the water column. Migration of

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the pollutants through the soil constitutes a completely different process of a much longer time scale and it goes beyond the scope of the present paper but is thoroughly studied in literature (see e.g. Rovdan, 2003 and the literature given there).

An experimental investigation conducted in the Upper Narew river flowing through the marshy area placed within the Narew National Park serves for the justification of the correctness of the presented modelling approach. The response of the stream to a slug injection of the tracer is presented in the form of the variation of concentration with time at the cross-sections downstream of the injection. The highly asymmetric shape of the concentration-time curves precludes from the application of the simplest Fick-type model (Sukhodolov et al. 2002). Therefore as the first approximation a variant of the storage-zone model is applied (see Czernuszenko, Rowiński 1997 and the references given there) where the storage is mostly caused by the adjacent wetlands. The applied model has been compared with the data obtained in a dye tracer test under steady state conditions. The model however allows for the treatment of unsteady flow conditions as well.

Usually research that focuses on water quality has two principal facets. The first relates to hydrologic and soil processes that affect water quality flowing through a wetland. The second facet considers the interaction of land management practices and water quality, as a basis for designing management practices that do not degrade water quality. The conducted modeling exercise is a preliminary task which hopefully will contribute in meeting the mentioned needs and the understanding of the basic processes in the nearest future.

MATHEMATICAL MODELING OF THE POLLUTION TRANSPORT

To describe the pattern of the pollution transport in a river reach in a wetland area some modeling concept has to be adopted. A proposed model will be successively fitted to the observed breakthrough curves on the reach-by-reach basis and reach-specific model parameters will be obtained. It constitutes the main idea for the analyses of the results of the present paper. Different methods of the interpretation of such model in respect to multi-thread channels have been given in Rowiński (2001). For the purpose of the subsequent analysis the following formulation of the model will be adopted. This model is traditionally developed by deriving the one-dimensional mass balance equation with source term in the form:

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} - D\frac{\partial^2 C}{\partial x^2} = \frac{\varepsilon}{T}\left(C_d - C\right) \qquad (1)$$

where C is the area-averaged concentration in the main stream, U is the area averaged mean stream velocity which is assumed to be constant along the given sub-reach, C_d is the concentration in the dead-zone, D is the constant dispersion coefficient, T and ε are additional constant coefficients. The latter represents the ratio of volume of stagnant areas (dead zones) to volume of mainstream for length unit of a river reach. The former will be explained below equation (3). Both concentrations C and C_d are normalized by the total mass of the solute discharged into the river, i.e. at any time t>0

$$\int_{-\infty}^{\infty} C(x,t)dx = 1 \quad \text{and} \quad \text{at any } x > 0 \quad \int_{-\infty}^{\infty} UC(x,t)dt = 1 \qquad (2)$$

On the left hand side of equation (1) the one-dimensional mathematical representation of basic processes governing the spread of passive admixture in flowing surface waters is given. These processes include advection, i.e. the downstream transport of solute mass at a mean velocity and dispersion - the spreading relative to the depth-averaged or cross-section averaged velocity due to movement with different velocities in different parts of the flow. The right side of equation (1) expresses the rate of concentration change due to mass-exchange between the mainstream and the stagnant areas which may for example be created by the marshy vegetation or wetlands in general existing in the direct neighborhood of the main channel. In other words an essential result of the transfer is that the solute is retained in the wetland areas. Taking into account the complexity of the river geometry in the area we may assume that various sets of constant coefficients represent the described situation in each subsection. The mentioned parameters are interpreted as "lumped" parameters that represent a spectrum of storage processes that occur simultaneously in multiple types of storage zones. Depending on the sign, the rate term represents the growth or the decrease of concentration in the main stream of the river. Assuming that the admixture is completely mixed within the storage zones, the mass-exchange balance between the dead zones and the main stream gives:

$$\frac{\partial C_d}{\partial t} = \frac{C - C_d}{T} \qquad (3)$$

The solution domain is the plane O*xt* limited by inequalities $0 \le x \le L$ and $t \ge 0$, where *L* is the length of the modeled channel reach. The model equations are complemented by the following

initial conditions:

$$C(x,t=0) = C_p(x) \qquad C_d(x,t=0) = C_{dp}(x) \quad \text{for } x \in [0,L] \qquad (4)$$

and boundary conditions:

$$C(x=0,t) = C_0(t) \qquad D\left.\frac{\partial C}{\partial x}\right|_{x=L} = 0 \qquad t \ge 0 \qquad (5)$$

We do not attend here to the question of the determination of the actual mean velocity along the channel and this is a question of a separate study, results of which will be published elsewhere.

Another problem is the evaluation of the empirical parameters occurring in the considered model. A number of approaches have been tried in respect to the river reach under consideration. For the estimation of parameters in the present study the use is made of the frequency response function derived for the system of equations (1-3). This function is the imaginary part of the transfer function, defined as the ratio of the Laplace transform of the output to the Laplace transform of the input under the assumption that the initial conditions are zero. Another approach based on the random global optimisation technique has been also recently tried providing similar results (Rowiński et al., 2004).

The parameter T may be interpreted as the penetration time of tracer into (or out) the storage zones and it is called a time constant of the system described by equation (3). It is easy to see that equation (1) and equation (3) converge to the Fickian equation when $\varepsilon \to 0$ and $T \to \infty$. The considered model has to be complemented with a set of initial and boundary conditions specific for the described situation. The influence of the various processes considered in the model on the anticipated breakthrough curves is given in Fig. 1.

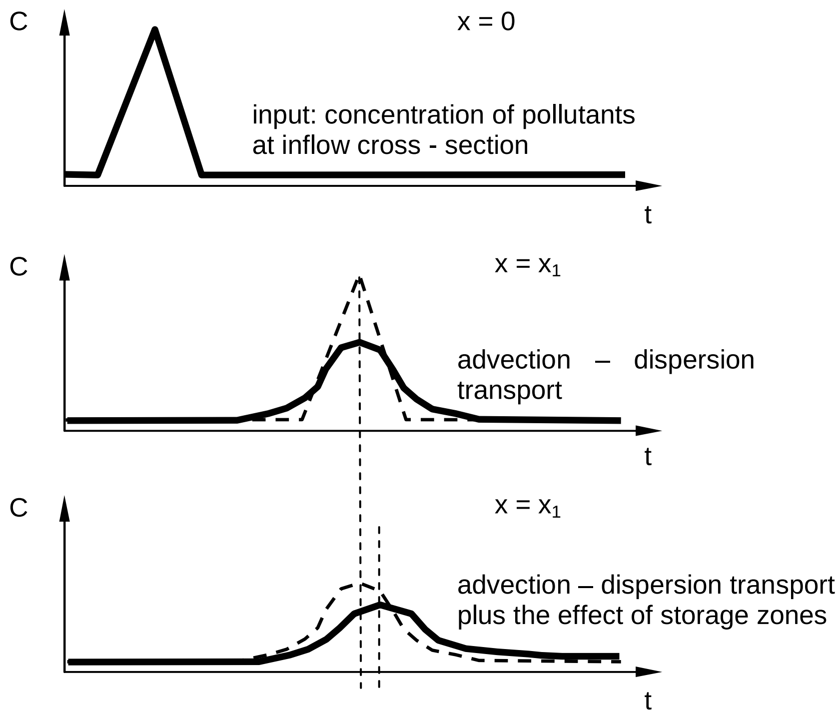

Figure 1. The influence of advection, dispersion and effect of storage zones on the breakthrough curves

CASE STUDY RESULTS

A tracer experiment was carried out in a meridional part of the Upper Narew River. The multichannel Narew River section extends in the marshy area from Suraż to Rzędziany villages and this part of the river constitutes the basis for the Narew National Park (NNP). Until the Rzędziany section the river has a natural character, since no drainage works have ever been done there (Mioduszewski, 2001). The only important unnatural factor influencing both the water quantity and quality in this area is the Siemianówka water reservoir built upstream, about 50 km from the Narew National Park. The river system within NNP maintains its absolutely unique character with its frequently branching and rejoining streams. The Narew valley in this area is characterized by a relatively flat bottom bordered by gentle slopes of low hills built mostly of glacial clays.

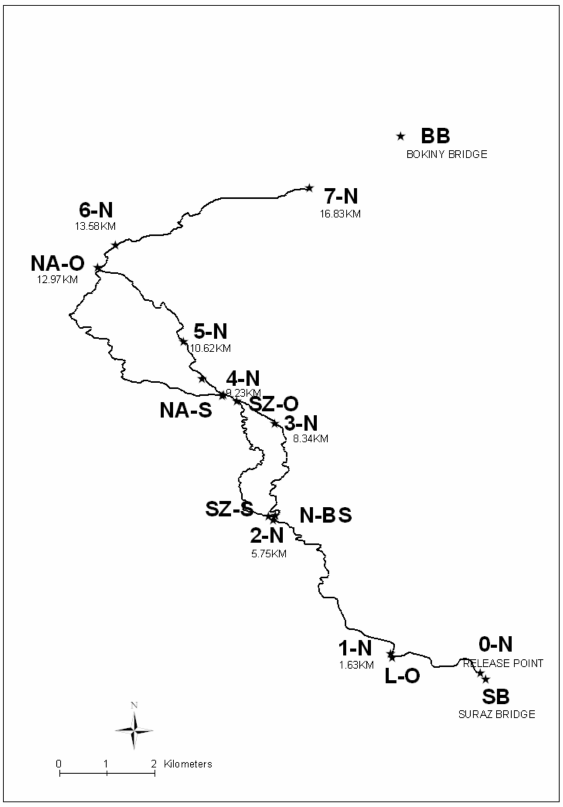

Figure 2. Map of the experimental reach of the Upper Narew River. Digits denote the number of cross-section, SB – Suraż Bridge, BB – Bokiny Bridge, N – Narew River, NA – Napiórka River, LO – Lisa outlet, SZ – Szołajdzianka River. The distances in km from the release point are marked on the map.

The present study has been concentrated on the initial reach of the river within NNP starting from the bridge in Suraż and with the last measuring site in Bokiny village and it extended along the main river stream over a distance of 16.8 km according to the GPS-reading (see Fig.2). The Upper Narew River in the considered meridional part is of an anastomosing type. The Narew channel meanders and it influences the dynamics of water flow. The onset of turbulent flow deflects some of the water towards the channels sides. As it reaches the side of the channel it is reflected back toward the opposite side of the channel. As the water changes side, it obviously also flows downstream, resulting in a zigzag flow line pattern.

Hydrological measurements were made in the end of May 2001. The details of the hydrological survey are given in (Rowiński et al., 2003). The conditions of river flow and ground supply were stable. Small precipitation didn't influence the increase of water level. The water levels registered by the water gauge in Suraż varied in the range from 126 to127 cm. The medium flow here in 1949-1995 is 189 cm, the lowest of medium flows is 153 cm. Therefore the water flow during measurements was much lower than the lowest of medium flows, and only slightly higher than the medium of low flows, which is 116 cm in Suraż. Similarly, the flow in Suraż Q = 5.104 m^3/s is not much higher than the medium low flow, which is 3.7 m^3/s.

Recognition of the streamwise velocity field was the main challenge for the hydrological survey. The knowledge of actual velocity distributions allowed also for the determination of the discharges at the selected cross-sections. Traditional methods that make use of current meters were utilized for the determination of point velocities. Point velocity distributions are usually in agreement with classical vertical velocity distributions with maximum values occurring in the range between the level 0.8H and the water surface. The maximum streamwise velocities did not occur at utmost verticals located close to the riverbanks. The reason is that the measuring cross-sections were selected at possibly straight river reaches in which the parallelity of water streams occurred. In general in the areas where meandering was observed, the maximum velocities usually occurred close to the convex riversides. Greater values of point velocities were observed below the Szołajdzianka branch down to the profile 6-N. The greatest mean and maximum velocity were measured at the cross-section 5-N.

Water surface slope along the whole river reach, slopes between measuring cross-sections, local water surface slopes, overbank parts of riverbed profiles and ordinates of the free surface were fixed by levelling in relation to provisional bench-marks levelled to a geodetic bench-mark in Suraż, in the Kronstadt reference system. The provisional bench-marks were installed in the measurement profiles except for the Bokiny profile, which is 10 cm below the bench-mark. Levelling of the section of the river was closed and checked. The deviation at the state benchmark in Bokiny was 50 mm, which is a very good result in technical levelling.

The flow rate and its spatial variation in the period of measurements as well as other hydraulic and topographic characteristics are shown in table 1, where the hydraulic radius, local water surface slopes, Manning coefficient, Froude and Reynolds numbers are given in respect to all measuring cross-sections. The roughness coefficient n varies in a relatively large range $0.032 < n < 0.194$. The smallest resistance to motion was observed in the profile 0-N, the largest one in profile 7-N, i.e. in Bokiny village. Such large value of coefficient n = 0.194 at the last measuring cross-section - Bokiny most likely results from a complicated and strongly differentiated character of the riverbed along the relatively short section. Particularly large were changes of the channel depth in the longitudinal direction. Observation at the Bokiny cross-section is not unique and such great values of the roughness Manning coefficient may occur in lowland rivers (e.g. Szkutnicki, 1996).

Table 1. Hydrological characteristics of the Narew River, and its main branches

River	Cross-section	Wetted area	Width	Average depth	Maximum depth	Average velocity	Maximum velocity	Flow rate
		A [m^2]	B [m]	T_m [m]	T_{max} [m]	V_m [m/s]	V_{max}[m/s]	Q [m^3/s]
Narew	0-N	14.37	39.00	0.37	0.70	0.355	0.596	5.104
Liza	L-O	0.07	0.99	0.07	0.18	0.196	0.301	0.014
Narew	1-N	31.07	23.00	1.35	1.97	0.163	0.209	5.069
Narew	2-N	19.23	14.20	1.35	2.20	0.271	0.390	5.220
Szołajdzianka	SZ-S	1.22	5.50	0.22	0.42	0.171	0.317	0.207
Narew	N-BS	16.29	15.00	1.09	1.67	0.310	0.472	5.052
Narew	3-N	16.13	21.30	0.76	1.05	0.305	0.467	4.917
Narew	4-N	21.25	24.20	0.88	1.31	0.237	0.390	5.030
Napiórka	NA-S	4.42	5.50	0.80	1.39	0.124	0.193	0.547
Napióreczka	NAP-S	0.74	3.00	0.25	0.32	0.049	0.085	0.037
Narew	5-N	11.87	17.80	0.67	1.00	0.405	0.679	4.812
Narew	6-N	20.23	21.20	0.95	1.30	0.277	0.498	5.597
Narew	7-N	44.63	25.00	1.79	2.67	0.122	0.328	5.430

The course of the tracer test was extorted by its needs, i.e. the evaluation of the threats by an accidental release of the pollutants at the downstream locations and by the economical and technical feasibility. Therefore the initial part of the stream where the solute mixes across the depth and the width of the river is ignored and the study is concerned with one-dimensional, longitudinal transport of the dye. Rutherford (1994) stresses that when studying longitudinal dispersion it is necessary to sample for long enough to measure the entire concentration versus time profile at each site and check for tracer loss and indeed it was extremely time consuming and made us to have people in the field for almost a week. The reason is the long tail associated with tracer becoming trapped in various river arms and bights and the classical dead zones. The method of instantaneous injection of the tracer was applied and it did not require the complex dosing facilities and allowed to obtain high initial concentrations of the tracer. The dye release consisted of 20 liters of 20% solution of Rhodamine WT, which was released at three points at the cross-section just downstream of the bridge at Suraż. Concentrations were measured at six transects corresponding to flow distances of 3.62 km, 8.34 km, 9.01 km, 9.23 km, 13.58 km, and 16.83 km (Fig.2). First cross-section was established at a distance at which 1D conditions were supposed to be achieved. During the early stages of a test, dye is visible to the naked eye, which facilitates sample collections. The dye was detected by using the field fluorometer Turner Design with continuous flow cuvette system on the one hand and also water samples were collected at sampling points. Continuous measurements were performed at two transects denoted as profile 2-N and profile 5-N. The measuring crew was equipped in fluorometers, graphical register and the pumps enforcing steady flow through the flow cell of the fluorometer. Measuring data were stored on graphical registers in the form of concentration distributions and then digitised to obtain relevant concentration time series.

Samples were collected to the glass bottles with Teflon-lined caps to prevent adsorption and were protected from sunlight. The dye concentration curves were registered until the complete decay of fluorescence, i.e. until the background concentrations were achieved. The resulting breakthrough curves are presented in

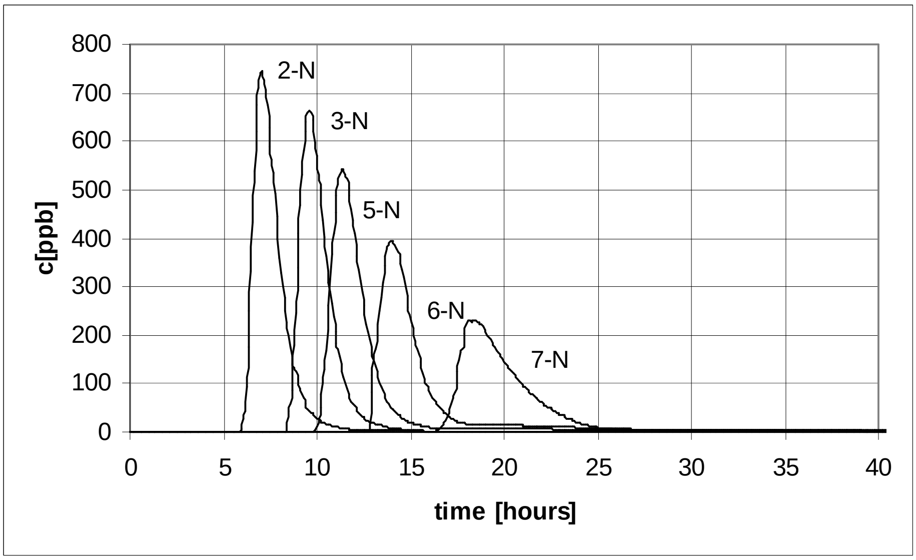

Figure 3. Observed breakthrough curves of Rhodamine WT in the stream water at measuring cross-section.

The described in the previous section model was fitted to the observed breakthrough curves and thus an evaluation of the model parameters was made. The fitting was performed at subreaches along the stream with the observed temporal concentration curves at one station as a boundary condition for the next one. The use was made of the frequency response function and the inverse fast Fourier transform.

Table 2. Parameters of the impulse response model

Parameters	**Sections**					
	[0-N, 2-N]	**[2-N, 3-N]**	**[3-N, 5-N]**	**[5-N, 6-N]**	**[6-N, 7-N]**	**[0-N, 7-N]**
D [km^2/h]	0.0027	0.0220	0.0051	0.0338	0.0034	0.0120
ε	0.0920	0.0120	0.7920	0.3690	0.2260	0.1020
T [h]	0.4530	0.6550	11.2570	7.0706	0.9030	1.4440
U [km/h]	0.5200	1.8400	0.4880	1.6200	0.7800	0.9190

The results of the described estimation procedure are given in table 3. Application of those parameters to the computations of temporal variations of concentrations at the given cross-sections lead to similar results as the ones experimentally observed. Fig.4 presents relevant examples of such computations.

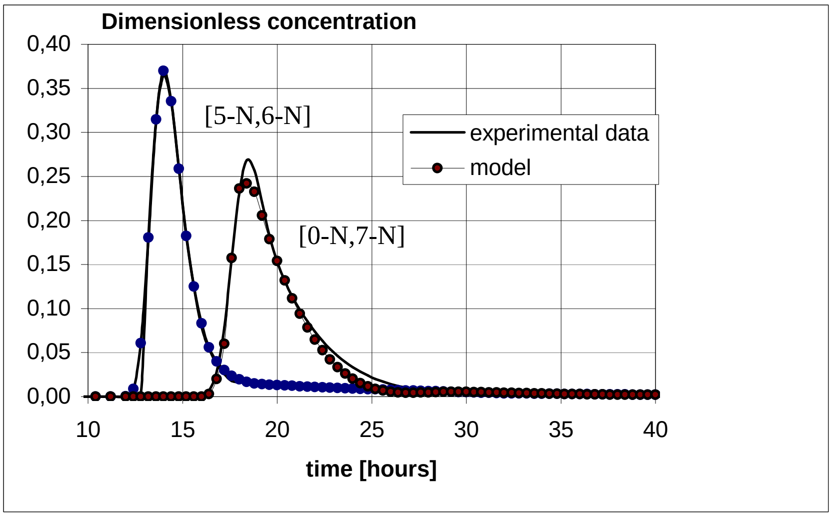

Figure 4. Comparison of measured solute concentrations with the modelling results.

Note that the evaluated dispersion coefficient is the smallest in the initial section (0.0027 km^2/h) and it assumes the highest values in the sub-reach [5-N,6-N], i.e. 0.0338 km^2/h. Such big differences are the result of high variability of geometrical and hydraulic conditions along the stream. Most of the quantitative analyses of the dispersion coefficient were conducted by means of the traditional Fick-type model and such results cannot be automatically transferred to the models that take into account the temporary storage of the admixture. Czernuszenko et al. (1998) showed that when natural rivers are considered, the dispersion coefficients obtained by means of the dead zone model are much smaller than the ones obtained with the use of traditional methods. It is caused that in the Fick-type models, the dispersion coefficient among others accounts for the non-uniformities and irregularities such as islands, rapids, deep pools, which obviously influence the pattern of the spread of pollution. It can be noticed that in the considered case, the dispersion coefficient increases together with the growth of the mean channel velocity. The parameters that account for the temporary storage of the dye vary along the river stream considerably as well. In the first sub-reaches the parameter ε is less than 0.1 and such values have been often observed in relatively regular rivers (Sukhodolov et al., 1997). Such values already testify about the presence of numerous storage zones in which the dye has been trapped and the time of penetration is represented by parameter T. These storage zones occur in the main stream itself. Also part of water and pollution penetrates the adjacent marshes with its specific vegetation which hinders the flow considerably (see Fig. 5).

Much higher values of ε below the station 3-N is caused by the migration of the part of the tracer to the river branch Szołajdzianka where the conditions for the transport of mass is much worse and therefore the concentrations curves at the station where the streams rejoin are characterized by long tails stretching upstream and this fact has to be reflected in the source term of Eq.1. Parameter ε and more exactly the ratio of ε ad T is decisive for the magnitude of this term. Note the extremely long time of penetration of the admixture in this river reach. Similar situation is observed when we deal with Napiórka and Napióreczka bifurcations. In this highly complicated part of the river the dead zone parameters and consequently the additional term in the advection-dispersion equation are responsible for the hindered transport of the dye through the slower (in comparison to the main stream) river branches penetrating the surrounding wetlands. Those river branches were much more vegetated and the solute needed much more time to overcome them. In the light of the presented model the river branches can be treated as additional storage zones, which superimpose with traditional dead zones created by the irregularities of the riverbed. Existence of sand bars and shoal patches, variability in roughness conditions influenced the increase of storage zone parameters. Moreover, the riparian vegetation extended over the width of 0.5-1.0 m, and in some cases like at the profiles 3-N, 5-N, 7-N over as much as 1.0 to 2.0 m of a wetted area. The last set of parameters provides an overview for the entire river reach under consideration and it gives averaged values determined for this highly changeable reach.

Figure 5. A typical stagnant area adjacent to the main stream of the Upper Narew river.

CONCLUSIONS

The usefulness of the pollution transport model including the processes of advection and dispersion within the river itself as well as the storage caused by adjacent marshy areas has been checked. The model results have been compared with the data obtained from a tracer test performed in the anastomosing type of river in the northern-eastern Poland. This model has been applied to conservative solutes but the achieved success encourages to extend the studies towards reactive solutes. The proposed model may serve as an alarm tool for the rivers wandering through wetlands.

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